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Influence of Tidal Inlets on Tsunami Waves in the Atlantic (Charente Region, France)

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Abstract: The French Atlantic coast seismicity is minor to moderate. Nevertheless, in western (north and central) part of France, the active tectonics related to the south Armorican and the Bay of Biscay context results sometimes in shallow earthquakes with magnitude above five (e.g., the Oleron seismic crisis, magnitude (local) = 5.2, 1972). The Charente region is featured by semi-diurnal tides that reach about six meters in height during the high tide period. Inlets are the main features of the Atlantic margin geomorphology nearby the Charente. Minor tsunamis have been observed and reported in the past. Here, we present a tsunami modelling computed with the TELEMAC package that solves the non linear shallow water equations. This work helps to identify the role of the inlets that characterize the Charente's geomorphology on water wave's propagation. A tidal model is considered while the tsunami simulation is performed. The modelling results show that the Antioche, the Maumusson and the Pertuis inlets protect the Charente coast from destructive waves.

Key words: Oleron Island, French Atlantic, inlet, tsunami, earthquake, modeling.

1. Introduction

The Charente Maritime Department is located in the French Atlantic coast (west-central part of France) (Fig. 1). Thanks to its maritime boundary (463 km in length), this region is particularly favored for specific economic activities such as oyster farming, salt marshes in the Re and Oleron islands and agricultural activities in the Poitevin marshes.

The French Atlantic margin is passive, marked by a smooth relief and major sediment accumulation. The present-day tectonic activity is very low. Nevertheless, a minor to moderate seismicity has been recorded in the past (e.g., the 1972 Oleron seismic crisis, magnitude = 5.2). Although the Charente-Maritime is not identified as a tsunami genic area, fishermen and inhabitants reported abnormal waves after the 1972 earthquake (local press, "Sud Ouest", 09/09/1972). According to previous studies [1, 2], the active fault for this event lies all along the Oleron Island (Dolus Fault, represented in red in the Fig. 1). The tectonics and the geomorphology of the Bay of Biscay result from (1) its opening and closure from the Cretaceous to present day and (2) the sedimentary fill coming from the main rivers located in the Aquitaine and Armorican Basin. Finally, several incised valley have been identified in the region and in particular between the Re and Oleron and in the Marennes-Oleron Basin as well [3]. The Marennes-Oleron Basin is a macro-tidal basin. The tides are semi-diurnal. During spring tides, the water wave rises up to six meters in height.

In this paper, we present a tsunami modeling for a worst case scenario to highlight the role of the coastal geomorphology for the Charente Maritime. The first section of this paper presents the regional setting that includes (1) the description of the tide inlet system and (2) the seismological context of the Poitou Charente. The Section 2 and 3 of this paper aim to

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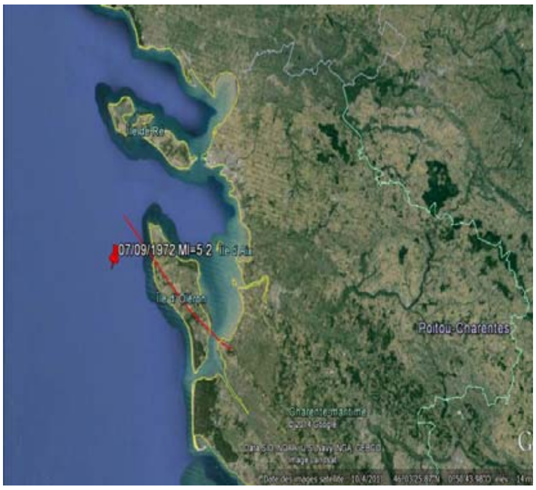


Fig. 1 The Charente-Maritime Region—Google Earth; red line: Dolus Fault.

develop the materials and methods we used for the numerical modeling tasks. The Section 4 presents the results obtained. Finally, the Section 5 and 6 focus on the impact of tsunami waves on the coastline and how the bathymetry and special features of the tide inlet system and the Bay of Biscay are critical to assess the tsunami risk in the Charente Maritime.

2. Regional Setting

2.1 The Marennes-Oleron Basin

In the Tertiary, tectonic caused depression and formation of the Marennes-Oleron Basin (Fig. 2). The Charente-Maritime region is marked by a tide inlet system (Fig. 2). The bottoms of the inlet area are characterized by very large foreshores (mostly 2-3 km and more) [3].

In the Maumusson inlet, the depths range generally between 10 and 20 m but can reach near 25 m. In the north, the Antioche inlet is characterized by a large (7-8 km) and a very deep trench (depths are greater than 10 m until 40 m in the axe). In the Breton inlet, the central part bottoms are around 10-20 m in depth whereas they reach 40-60 m in depth in the north of the Re island.

In the offshore, the bottom slope is weak and 20 m in depth are reached only near 8-10 km from the coast [3]. An important hydrographic network is connected to the inlet area. The Charente River flows into the Antioche inlet and the Seudre River into the Maumusson inlet (Fig. 2).

The circulation in this region is dominated by semi-diurnal tide with a spring tidal range rising up to six meters. It is a macrotidal region (Fig. 3).

2.2 The Seismological Setting

The passive margin of the Atlantic Ocean and the Bay of Biscay are the location of intraplate shallow earthquakes. Most of the events recorded in the Charente region are compressional or strike-slip, with a Northeast to East trending tensional-axis [1].

This seismogenic area is marked by quaternary structural accidents such as the Dolus Fault represented in red in the Fig. 1 [1, 4]. The active tectonics in west-central France reveals inherited features from the Hercynian Orogeny and the Armorican Massif and the opening of the Bay of Biscay [1].

Mazabraud et al. [1] highlighted that Northeast-Southwest extensional stress in northwestern part of the south Armorican Massif generates extension with a small dextral component on the northern part of south Armorican Shear zone. They reported as well as that the southern branch of the south Armorican Shear zone is striking more North-South in the Charente, the strike-slip component becomes more important [1].

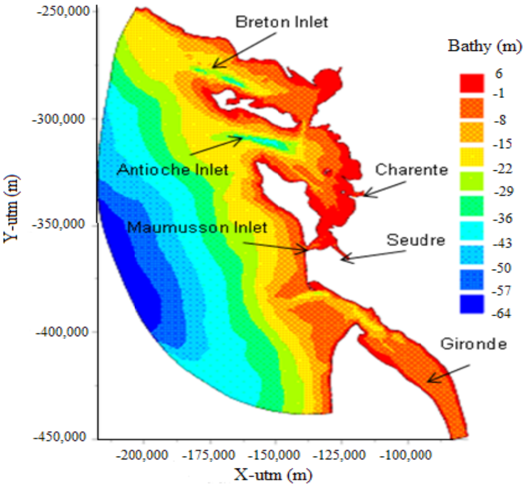


Fig. 2 Bathymetry of the studied area.

(a) (b)

Fig. 3 (a): Low tide level in La Rochelle city (70 cm estimated by the marine oceanographic and hydrographic service (SHOM) 12: 31, August 31, 2004); (b): high tide level (6.40 m estimated by the SHOM at 18: 36, August 31, 2004).

On September 1972, a seismic crisis struck the Oleron Island (45°58′ N, 1°32′ W; M_L = 5.2) The macroseismic intensity Io was evaluated to VII degrees [1, 2]. Mazabraud et al. showed that the 1972 Oleron Island swarm contrasts with the surrounding more diffuse seismicity [1]. They identified that this seismic crisis lasted more than 10 years and was represented by five distinct focal mechanisms. The main shock is normal with a slight dextral strike-slip component [1, 2]. One of the fault plane solutions consists of a purely extensional motion [1].

The 1972 Oleron main shock triggered tsunami waves that were observed in the Re Island. A minor impact of the tsunami in the Re and Oleron islands was observed in the aftermath of the September 1972 main shock. Waves were observed and reported in a small harbor in Ars en Re (Couarde, Re Island).

Fishermen heard a rumble, felt the tremor and reported that the sea level that was low at that time suddenly rose up to 60 cm in height. Small fishes were jumping out of the water. The local newspaper "Sud Ouest" reported on the 9th of September 1972 that a shark stranded and was found dead in the northern part of the Oleron coast. It is reported that this shark has been thrown in the net of fishermen because of abnormal water waves. In the Marennes district (Oleron Island), the mayor of Bourcefranc noted as well a slight increase of the sea-level when the earthquake hit the region. The sea bottom displacement was related to structural accidents due to the hercynian orogeny and mostly oriented E-W to ESE-WNE [1, 2].

Minor tsunamis have already been observed and reported in the past near La Rochelle city. In 1875 and 1882, historical observations reported the presence of small seismic water waves with height measuring 80 cm and 95 cm respectively [5].

3. Methodology

3.1 The Water Waves Modeling

The water waves are simulated with the TELEMAC-2D software package [6, 7]. The TELEMAC system includes interconnected software to simulate the waves' propagation for shallow water models [6-8]. This program is based on the long wave theory. It is a non-linear depth-averaged finite element solver of the Saint Venant hydrodynamic equations (conservation law, continuity and momentum equations):

$$\frac{\partial h}{\partial t} + \boldsymbol{u}.\nabla(h) + h\,\mathrm{div}(u) = S_h \qquad (1)$$

$$\frac{\partial u}{\partial t} + \boldsymbol{u}.\nabla(u) = -\mathrm{g}\frac{\partial Z}{\partial \mathrm{x}} + S_x + \frac{1}{h}\mathrm{div}(\mathrm{h}\boldsymbol{v_t}\boldsymbol{\nabla}u) \qquad (2)$$

$$\frac{\partial v}{\partial t} + \boldsymbol{u}.\nabla(v) = -g\frac{\partial Z}{\partial y} + S_y + \frac{1}{h}\mathrm{div}(h\boldsymbol{v_t}\boldsymbol{\nabla}v) \qquad (3)$$

where, *h* (meters) is the water depth; *u* and *v* (m/s) are the velocity components in the x and y axis directions respectively; g (m/s^2) is the gravity acceleration; Z (m) is the free surface elevation; t (s) is the time; S_h (m/s) and, S_x (m/s^2) and S_y (m/s^2) are source terms.

Firstly, the mesh is generated from the assembly of triangles elements with the program Matisse [8, 9]. Then, the code TELEMAC-2D solves the hydrodynamic Eqs. (1)-(3) using the finite element method for the output grid (Fig. 4).

3.2 Tsunami Simulation and Tide Model

Tidal and tsunami waves are long water waves that can be both reproduced by the TELEMAC-2D software. Kowalik et al. [10] demonstrated that tide and tsunami that propagate in a channel can be superposed in a linear fashion. In the Charente Maritime, the combination of these two waves is computed considering a subroutine for initial conditions and the tide model.

In this work, the Charente Maritime tide model was simulated at first. The calculation process was stopped to introduce the earthquake's onset conditions. Then, the water waves' simulation continued so that the hydrodynamic modeling was carried out for a couple of days that included the earthquake's event.

3.2.1 The Tsunami Modeling

The tsunami source here considered is an undersea co-seismic vertical displacement. In general, strike-slip fault motions do not trigger sea-bottom deformation enough to produce a significant rising of the free water surface. Nevertheless, for the Charente region, the 1972 Oleron seismic crisis is a good example of local tsunami occurrence. Therefore, the tsunami modeling task is performed by considering the seismological parameters determined for the Oleron seismic sequence.

The seabed deformation is estimated from a software that calculates the displacement field considering the Okada formalism [11, 12]. The fault geometry and the input parameters are determined from classical seismological empirical relationships [11]. Finally, the initial water surface deformation is estimated from the dislocation modeling results.

The water surface elevation due to the vertical co-seismic displacement is an instantaneous process. Therefore, the vertical sea bottom displacement component is translated to the free water surface to calculate the triggered seismic water waves using the hereafter formulas [13, 14]. These two equations (Eqs. (5) and (6)) are introduced in a subroutine of the Telemac software to consider the initial water height at the onset of the earthquake for the epicentral area.

$$\eta(x, t = 0) = as^2 \left[\sqrt{\left(\frac{3a}{4d^3}\right)} x \right] \qquad (5)$$

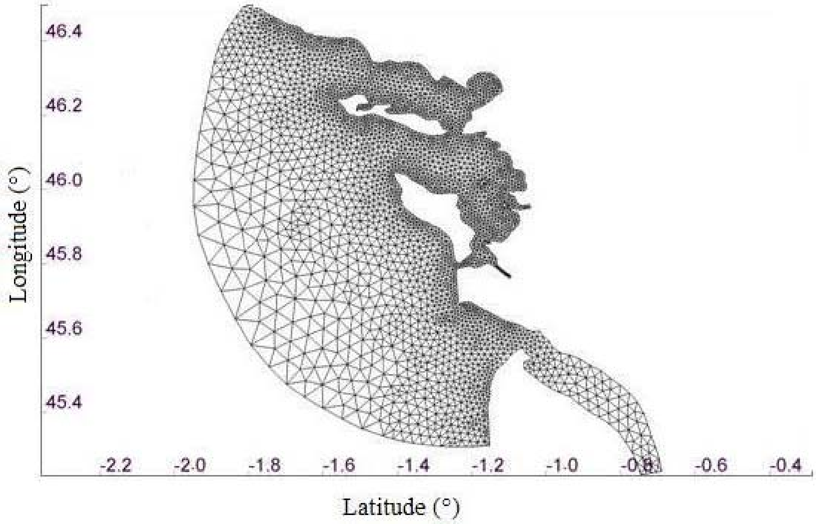


Fig. 4 The Charente-Maritime finite element method [9].

$$u(x, t = 0) = c\frac{\eta(x, 0)}{(d + \eta)} \quad (6)$$

where, $\eta(x, t = 0)$ is the initial surface water elevation in the x-axis direction (m); $\boldsymbol{u}$ $(x, t = 0)$ is the initial fluid velocity in the x-axis direction (m/s); a is the vertical coseismic displacement (m); d is the ocean depth (m); c is the celerity defined by the formula $c^2 = g\,(d + a)$ (m/s); g is the universal gravity constant.

3.2.2 The Charente Maritime Tide Model

Tide inlet system consists of narrow connections to the open sea where the rising of the sea level is controlled by the tide force. The tide force results from the interaction between solar and lunar relatively to the earth's orbital position. The theoretical tide can be predicted at any location on the earth as a sum of a number of harmonic terms contained in the polynomial expansion representation of the tide producing forces. Hence, tidal waves are commonly estimated from the harmonic development of the tide potential. Mathematical expressions of tidal waves show distinct types of waves characterized by a phase and a period. Tide cycles can then be defined in some regions relatively to the positions of the earth, the moon and the sun (diurnal, semi-diurnal, etc.).

In the Charente Maritime, the main component of the tidal waves is represented by the M2 constituent. This type of wave determines a semi-diurnal cycle with a period of 12 h and 25 min. It is a lunar component.

The tidal range varies between 2-6 m in height. To compute the tide model, Nicolle et al. [9] used the harmonic constants from the French national hydraulic laboratory catalog.

In this study, we reproduced the same state of the ocean as it was before the 1972 Oleron seismic crisis. The September 1972 period corresponds to spring tides. The tide model was adapted to consider the appropriate astronomical arguments.

4. Results

The undersea earthquake modeling for a magnitude 5.2 earthquake shows the sea bottom deformation is insignificant and therefore cannot produce tsunami waves from the numerical modeling carried out with the TELEMAC-2D software. For that reason, we only represent here the results obtained for a 6.5 magnitude earthquake offshore the Oleron Island (rake = -80° and focal depth = 7 km) (worst case scenario).

4.1 The September 1972 Charente Tide Model

The effects of the tides were considered to reproduce the free water surface for the September 1972. The computation was programmed for six days (September 3, 1972-September 9, 1972). The tidal wave height profile simulated at the epicentral area is depicted in Fig. 5. The propagation of the tides across the whole region is shown in Fig. 6.

The simulation clearly shows the semi-diurnal feature for the M2 tidal wave (Fig. 5). Here the tidal range is about 5.5 m in height. This value is in good agreement with the observations from the SHOM catalog and the tides that are usually observed and recorded during spring tides. The model well reproduced that the tide was low on September 7, 1972 in the Re and Oleron islands (Fig. 6). On the other hand, the Charente coast and the La Rochelle city were marked by a higher tide level.

4.2 The Tsunami Modeling

At the time the earthquake hit the region, the tide was low (Fig. 6). In the epicentral area, the water wave rose suddenly by 4 m and reached 5.5 m in height (Fig. 7). The rising of the sea due to the tides is shown during the next few hours. The tidal range decreases just after the onset of the earthquake that goes back to its normal value for this period (Fig. 6). The wave period shortens as soon as the co-seismic displacement is introduced in the model (Fig. 7). Meanwhile, the tidal range decrease and the level of the free surface is about five meters during a couple of hours and days.

The semi-diurnal period is 12 h and 25 min

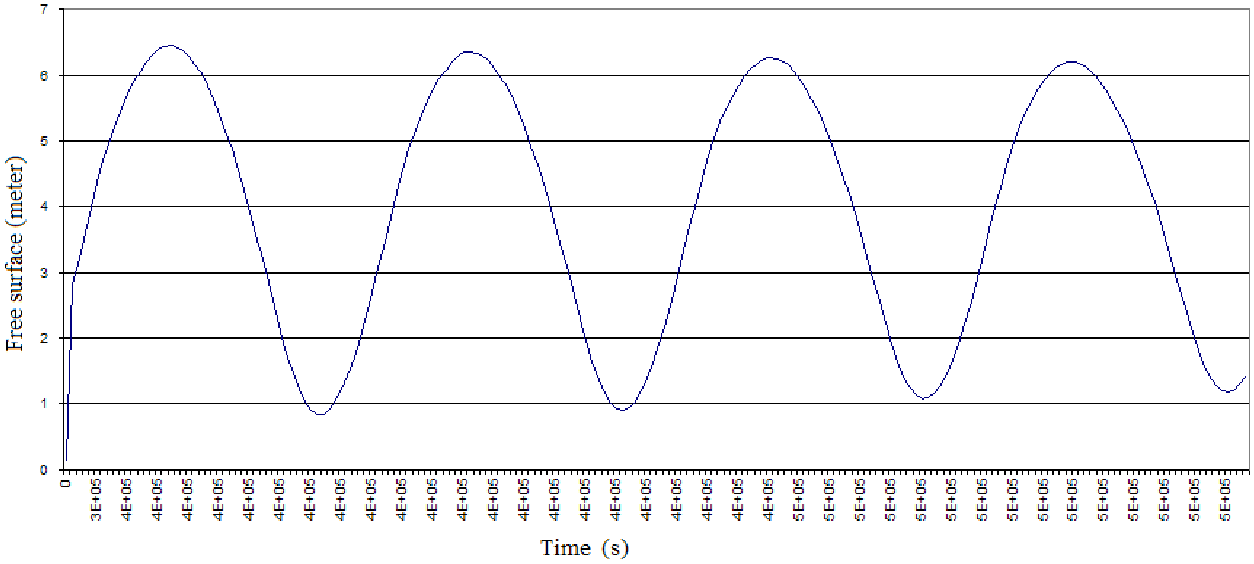


Fig. 5 The Charente-Maritime tide model for September 1972 (September 7, 1972-September 8, 1972). This curve corresponds to the wave height estimated at the 1972 main shock epicenter.

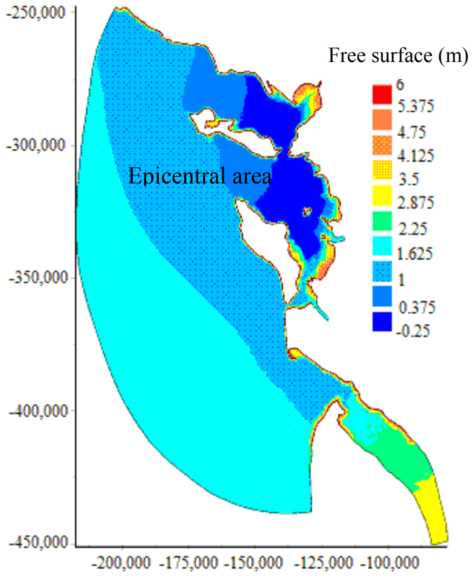


Fig. 6 The 1972 Charente Maritime tide model before the introduction of the earthquake initial conditions (low-tide level). The *x*-axis and *y*-axis are the coordinates expressed in meters.

in the Charente Maritime region. The results here obtained show the tide is disturbed for the first couple of hours after the earthquake onset (Fig. 6). Later, it increases slightly to go back to its normal value. The tsunami wave periods here are relatively short and not typical for destructive tsunami waves. Nevertheless, the waves' velocity is a factor for potential slight damage in the coast.

The propagation of the tsunami waves across the whole region is shown in Fig. 8. The tsunami waves follow the bathymetry of the region. As soon as the seismic dislocation is introduced, the water surface rises up to 7 m in the northwest of the Oleron Island. The tidal height computed ranges around 6 m in the southwest of the Re Island (Fig. 8a). During the first quarter of an hour, the highest tsunami waves mostly propagated to the south west of the Oleron Island (Fig. 8b) (about 7 m in height).

Thirty minutes after the occurrence of the earthquake, the abnormal elevated sea-level is concentrated in the southwest of the Oleron Island and in southeast and center of the Re Island (see Fig. 8c). Finally, only 45 min after the occurrence of the earthquake, the propagation of the tsunami has reached the port of La Pallice (see Fig. 8d).

The wave heights computed for the whole region are higher in the western part of the Oleron Islands. In the Re Island, they do not reach more than6 m in height, which is the water surface value during the high tide period.

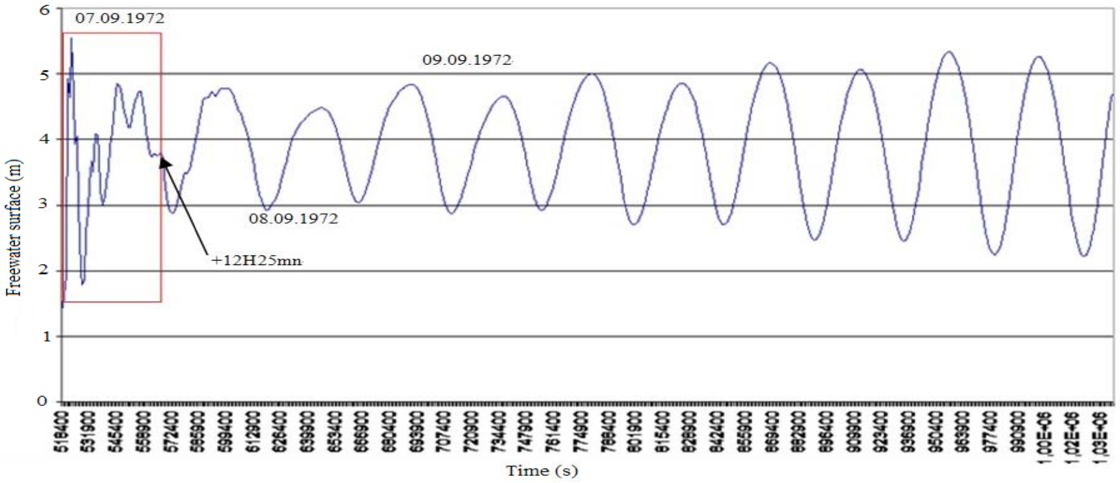
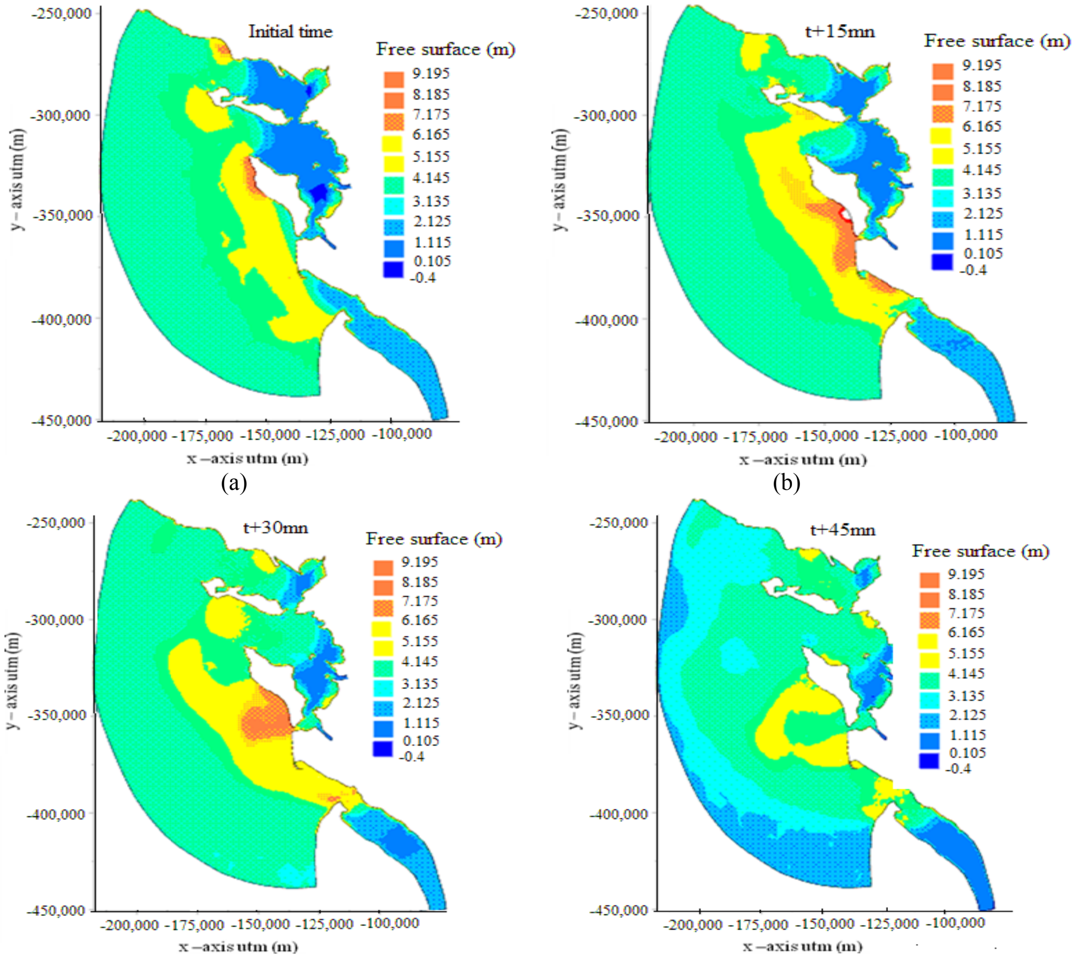


Fig. 7 Wave height profile computed at the epicenter. The bottom axis represent the time (s). The earthquake is introduced 6 days after the beginning of the tide modeling. Therefore, the *x*-axis begins at *T* = 518,400 s which corresponds to the September 7, 1972 (low tide level).



(a) (b)

(c) (d)

Fig. 8 Tsunami waves propagation computed. The bottom axis represents the *x*-coordinates expressed in meters (Universal Transverse Mercator coordinate system). (a): snapshot of the tsunami wave generation—initial time; (b): snapshot of the tsunami wave propagation—15 min after the onset of the earthquake; (c): snapshot of the tsunami wave propagation—30 min later; (d) snapshot of the tsunami wave propagation—45 min after the onset of the earthquake .

5. Discussion

The results obtained show that the inlet zone (Pertuis Charentais) constrain the tsunami waves' propagation. The inlet zone acts as a natural barrier and protects the coastline from destructive waves. The water waves mainly propagated along the western part of the Oleron Island.

In the Charente Maritime, the semi-diurnal cycle controls the sea-level variation twice a day. Bottom friction and shape of the tidal basin constrain waves' amplitude. The wave energy is trapped. Consequently, at the continental coastline, the estimated free surface elevation decreases.

The results obtained are explained from the geomorphology of the region. The 1972 earthquake source tested was located in the Atlantic Ocean (45˚58′ N, 1˚32′ W) at a focal depth of 7 km. It is then common that while reaching shallower areas, tsunami waves' wavelengths decrease and amplitudes and velocities increase. In the Charente region case study, the Antioche and the Breton inlets separate the Oleron Island from the continental coast and the Oleron Island from the Re and continental coastline respectively. Hence, as the tsunami waves reach La Rochelle city, the wave height is attenuated by the topography. The three inlets reduce the impact of the waves in central western part of the French Atlantic coast. In particular, the Antioche inlet is the one that protects the La Rochelle city from damaging coastal tsunami waves. Nevertheless, the rivers that flow into the continent (Charente and Seudre) might show disturbances. Past literatures indicate small tsunami occurrence in the coast with flooding in the Seudre River [5].

The morphology of a tide basin evolves according to sediment discharge. In the Charente-Maritime, the shoreline topography is constrained by the sediment infilling from the Charente and Seudre rivers. The tide plays an important role on the sediment transport. Hence, tidal inlet systems influence water waves' propagation.

Finally, the North East Atlantic has been the location of large-scale tsunami events triggered by sources located in the Gorringe Bank [13-15]. The Bay of Biscay is marked by deep-submarine canyons [16]. Sedimentation processes and short-duration events' datation in these geological structures could help to better analyse turbidity current's origins in the region. Moreover, the incised-valleys identified in the inner part of the Bay of Biscay [4] could definitely bring some insightful information for the September 1972 abnormal waves in the Re and Oleron islands.

6. Conclusion

Tide and tsunami waves are modeled through the long wave theory. They are linearly superposed. All computations were carried out with the Telemac software. The shallow water model here considered to use the hydrodynamic equations from St-Venant.

This study reveals that a tsunami hazard exists in the region. On the one hand, the continent coast looks to be well preserved from tsunami waves due to the geomorphology of the inlets (Pertuis, Antioche and Maumusson). The Charente-Maritime tidal inlet system acts as a natural barrier. On the other one, based on the 1972 scenario (rake = -80°), the western coast of the Oleron island might be at risk. The Charente Maritime region is famous for its swamps, salt, oyster and mussels culture. Hence, parts of the shoreline are dedicated to these activities. Moreover, the Re and Oleron Islands are the locations of numerous secondary houses for inhabitants who spend only a few months or week-ends for their vacations and tourism.

Finally, the scenario tested concerns the northwestern part of the island. It could be interesting to compute the effect of tsunami waves in the south and eastern part of the island. The inner parts of the Bay of Biscay include regions where sediments motions play a role in water currents for the Charente Maritime region. Although the seismicity is not the main hazard for this sector, combinations between earthquake and slides due to turbidity currents would help to better assess the tsunami risk for the Bay of Biscay and the French Atlantic. Breakwater damage and flooding risk could generate an impact for the economical activities in the region.

Acknowledgments

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